

MODIS reflective and active fire data for burn mapping at regional level

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Keywords: MODIS, spectral index, active fire, patch analyst

ABSTRACT: This paper presents an analysis on the forest fires occurred in Galicia (northwest Spain) in August 2006, when nearly 930km² were almost entirely burned over the course of eight days. This study presents an algorithm for burn mapping that synergistically combines remotely-sensed reflectance and active fire data as measured by the MODIS (MODerate resolution Imaging Spectrometer) sensor on board Terra NASA (National Aeronautics and Space Administration) satellite. Burned area data collected from this work was compared to official fires statistics from the Spanish Ministry of Environment and to perimeters that were derived using a high spatial resolution satellite image.

1 INTRODUCTION

Forest fires are a major source of concern not only for environmental reasons, but also those including economy, society and human safety in many parts of the world. Each year, this phenomenon affects millions of hectares of forests around the world. Forest fire effects at a local scale alter the ecosystem functionality due to the fact that fire plays an essential role in vegetation composition, biodiversity, soil erosion and water cycle, moreover, this phenomenon generate an important landscape impact (Pyne *et al.*, 1996). In addition, forest fires release a significant amount of greenhouse gases, particulates and aerosol emissions into the atmosphere, which significantly increases the anthropogenic CO₂ emissions (Levine, 1991).

The use of remote sensing data provides temporal and spatial coverage of biomass burning without costly and intense fieldwork. The resulting information is suitable for its integration into a Geographic Information System (GIS) which allows the storage and processing of large volumes of spatial data (Chuvieco, 1996) as well as the production of spatial analysis (Sunar and Özkan, 2001). Related to forest fires, remote sensing data provide information on environmental

conditions before, during and after a fire occurs. The range of remote sensing methods dealing with scar mapping includes among others: (i) differencing of pre- and post-fires original bands or indices (Key and Benson, 1999; Loboda *et al.*, 2007), (ii) thresholding of original bands or indices (Hall *et al.*, 1980; González-Alonso and Merino-de-Miguel, 2008), (iii) unsupervised or supervised classification of original bands or indices (Milne, 1986; Miller and Yool, 2002), (iv) using active fire detections (Justice *et al.*, 2002; Giglio *et al.*, 2003), (v) spectral mixing analysis (Cochrane and Souza, 1998; González-Alonso *et al.*, 2007), (vi) time series analysis (Milne, 1986; Roy *et al.*, 2002; Roy *et al.*, 2005), etc.

Among the different methods for burn mapping by means of reflectance satellite data, the use of spectral indices is one of the most widespread. Vegetation indices (e.g. NDVI - Normalized Difference Vegetation Index), whose estimation typically involves data from the red and near-infrared (NIR) bands, have been commonly used to derive vegetation properties but also to discriminate and map burned areas. According to Lentile *et al.* (2006), in most environments and fire regimes and at the spatial resolution of most satellite sensors (>30m), burned vegetation results in a drastic reduction in near-infrared (NIR) surface reflectance, which is typically accompanied by a rise in short wave infrared (SWIR) reflectance. In this way, there arose some spectral indices that integrated the NIR and SWIR bands; both of which register the strongest response, albeit in opposite ways, to burning (Roldán-Zamarrón *et al.*, 2006). This is the case of the Normalized Burn Ratio (NBR) and the differenced NBR (dNBR), developed by Key and Benson (1999) and the MODIS Burned Area Index (BAIM), developed by Martín *et al.* (2006).

In addition to the use of spectral indices, several studies have showed the utility of active fire detections for burn mapping. In active fire detection, fire thermal energy, as measured by mid-infrared channels, is used to identify active fires. In a second step, scar mapping is developed based for example in the total number of active fires (Pozo *et al.*, 1997). However, the temporal and spatial patterns of biomass burning cannot be estimated reliably from active fire data, as the satellite may not overpass at the time of the fire, or the fire may be obscured due to cloud cover or dense smoke (Roy *et al.*, 2002). This difficulty can be solved through the combination of active fire information together with spectral indices (Roy *et al.*, 1999; Fraser *et al.*, 2000; Al-Rawi *et al.*, 2001; Pu *et al.*, 2004).

The work presented here assesses the estimation and mapping of burned areas in Galicia (northwest Spain) in 2006 using a method that integrates a spectral index with active fire data, both as derived from MODIS data. In a second step, the resulting 500m spatial resolution MODIS-based scar map is validated using an 56m spatial resolution AWiFS (Advanced Wide Field Sensor) -based scar map that was derived in a previous research (González-Alonso and Merino-de-Miguel, 2008).

2 STUDY AREA AND DATASET DESCRIPTION

The approach is applied here to Galicia (northwest Spain, Figure 1) where hundreds of forest fires occurred during the first days of August 2006. This region, situated in the northwest of the Iberian Peninsula, just to the north of Portugal, is one of the most humid parts of Spain. The study area covers 29,681.65km², almost 70% of which, according to the Third National Forest

Inventory (1997-2006), is classified as 'forested', with 64% being tree-covered (conifers and eucalyptuses mainly). In this region, woodland fires are usually small but frequent. In fact, Galicia is undoubtedly the region with the greatest concentration of wildfires in Spain. During August 2006, nearly 930km² were almost entirely burned over the course of eight days, producing significant economic losses and severe social upheaval. It is thought that about 90% of the forest fires were caused by people.

Three types of data were used for this work: (i) a post-fire satellite image, (ii) active fire data and (iii) ancillary maps and information. We used one post-fire image from the MODIS sensor onboard the NASA Terra satellite dated the 21st of August 2006 (Figure 1c), as well as MODIS active fire data for the whole 2006 year until the 21st of August 2006 (Figure 1b). The ancillary maps and information we used consisted of the CORINE Land Cover Database (CLC2000) at 1:100,000 scale and a digital map on Eco-regions at 1:100,000 scale.

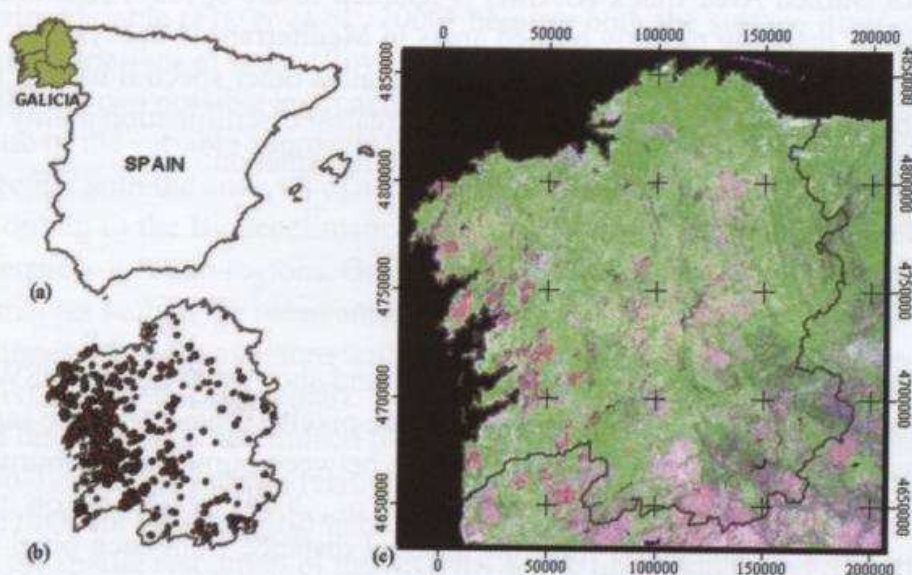


Figure 1. (a) Study area (Galicia) within the Spanish territory, (b) MODIS active fire locations (dated 1st January to 21st August 2006) and (c) MODIS post-fire image (dated 21st August 2006; RGB composition: 721; UTM – Zone 30 – ED50 coordinate system)

MODIS is a sensor onboard Terra and Aqua satellites with more than 30 channels at variable spatial resolutions (250, 500 and 1000m). We used one post-fire MODIS image that was downloaded from the EOS Data Gateway free of charge and it consisted of atmospherically-corrected surface reflectances in the optical range (7 bands, visible to shortwave-infrared wavelengths) at 500m spatial resolution (MOD09GHK). The MODIS Hotspots / Active Fire Detections (NASA / University of Maryland, 2002), as provided free of charge through the Internet, consisted of a set of shape files (one per year) with one record per active fire. Information related to each active fire included: location (latitude and longitude), date, time, confidence level and satellite involved (Terra or Aqua). The particular area in question, Galicia, (almost thirty thousand square kilometers) experienced 3,563 active fires between the 1st of January 2006 and the 21st of August 2006, 95% of which concentrated during the first twenty days of August 2006. A general description

of the MODIS fire products can be found in Justice *et al.* (2002). A detailed description of the MODIS active fire detection algorithm (version 4) can be found in Giglio *et al.* (2003).

3 METHODS

3.1 Development of a burned area mapping algorithm using MODIS reflectance and active fire data

All burned area estimation and mapping followed four steps: (i) Burned Area Index (BAIM) calculation using the MODIS reflectance image, (ii) BAIM threshold establishment, (iii) CLC2000 mask application and (iv) active fire analysis for final burned area map production. Image and data processing was carried out using ENVI 4.4, ArcView 3.2 and ArcGIS 9.2 software packages.

The MODIS Burned Area Index (BAIM) is adapted to the spectral resolution of MODIS reflective bands for mapping recently burned areas in Mediterranean ecosystems. The utility of the BAIM index to map burned areas was assessed against other spectral indices using MODIS data over the Iberian Peninsula and it provided the greatest discrimination ability (Martín *et al.*, 2006). The BAIM index is estimated using the following equation:

$$BAIM = \frac{1}{(\rho_{c_{nir}} - \rho_{nir})^2 + (\rho_{c_{swir}} - \rho_{swir})^2} \quad (1)$$

where $\rho_{c_{nir}}$ and $\rho_{c_{swir}}$ are the near-infrared (NIR) and shortwave-infrared (SWIR) reference reflectance values, respectively, and ρ_{nir} and ρ_{swir} are the pixel reflectances in the same bands. The BAIM index was specifically defined to discriminate between burned and unburned areas using data from the Terra&Aqua MODIS sensor (Martín *et al.*, 2006). It is based on its predecessor, the BAI index, which is 'computed from the spectral distance from each pixel to a reference spectral point, where recently burned areas tend to converge' (Chuvieco *et al.*, 2002). The BAIM uses 'concentric distances to a convergence point, defined from radiative properties of recently burned areas in the NIR and SWIR bands' (Martín *et al.*, 2006). It is calculated using pixel reflectance values in the NIR (MODIS band 2 at 0.841-0.876 μ m) and SWIR (MODIS band 7 at 2.105-2.155 μ m) bands as well as using NIR and SWIR reference reflectance values, those corresponding to the aforementioned convergence point. Such reference values are usually calculated based on the literature available and the analysis of several sets of satellite sensor images (Chuvieco *et al.*, 2002).

For the present work, reference reflectance values were calculated using the MODIS image itself. To do so, we used the statistical distribution of burned pixels reflectances, as extracted from the relevant bands (band 2 in the NIR and band 7 in the SWIR), by means of manual digitalization of more than 50 training areas. The digitalization process was carried out by an expert throughout the study area using both the original bands (displayed using an RGB composite) and some spectral indices (NDVI and NBR).

Van Wagendonk *et al.* (2004) showed in their work on fire severity assessment using AVIRIS and Landsat ETM+ data that, the higher the fire severity, the greater the negative response to fire

in the NIR wavelengths and the greater the positive response to fire in the SWIR. Therefore, if we are looking for 'for-sure-burned' pixels within the MODIS training areas because those pixels would give us the best definition of the BAIM index, lower values are the most telling in the case of NIR bands, while the same is true of greater values in the case of SWIR bands. In this way we would be maximizing the distance between burned pixels and other potentially confusing land uses. In practice, we defined reference reflectance in the NIR (pcnir) as the 'pnir value for 5% of accumulated probability (5 percentile, burned NIR reflectance distribution)' and reference reflectance in the SWIR (pcswir) as the 'pswir value for 95% of accumulated probability (95 percentile, burned SWIR reflectance distribution)'. We used the 5% and 95% of accumulated probability instead of the minimum and maximum respectively, in order to screen out any noise. Resulting convergence values were 0.07 and 0.20 for the NIR and SWIR bands, respectively.

After the BAIM index was calculated, a suitable threshold had to be established to distinguish between burned and unburned pixels. It is recognized that an effective threshold for separating burns is spatially variable (Fraser *et al.*, 2000) because both the surface itself and the sensing system introduce variations in space (Roy *et al.*, 2002). All the studies carried out on this subject have used one of the two possible approaches of fixed or variable thresholds. Many authors have favoured the use of the variable approach, but in this study we have opted for the fixed approach firstly, and together with the analysis of a stratification variable prior to threshold determination secondly. According to the Biogeoclimatic Classification of Spain (Elena Rosselló, 1997), that classifies the territory into eco-regions, Galicia can be divided into two homogeneous parts based on climatic variables such as the mean annual temperature and the annual days of snow and frost in a year. For brevity, these two regions will be named as eco-region 1 (warmer, more humid) and eco-region 2 (colder, dryer, continental).

The BAIM threshold was determined in all the cases: Galicia, eco-region 1 and eco-region 2, based on the analysis of the best correlation between 'burned area' and 'number of accumulated MODIS active fires' for different grid sizes (1, 2, 3, 4, 8 and 10km). We started with the 1km grid size, as this is the spatial resolution of the MODIS active fire product, and then kept on increasing grid size regularly up to 10km (Galicia is covered by 363 cells of 10x10km). It was found that the coarser the spatial resolution of the grid, the better the correlation between 'burned area' and 'number of accumulated MODIS active fires' (results are presented for some grid sizes and threshold values in tables 1 and 2). 'Burned area' was established retaining only those polygons containing at least one MODIS active fire inside. This technique may not identify all burns, but those identified are certain to be truly burned. BAIM threshold values originally considered for the analysis were: 30, 35, 40, 41, 42, 43, 44, 45, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60 and 65. Subsequently, the best correlation results, expressed in terms of the coefficient of determination, were found for BAIM threshold values of 55 (Galicia), 45 (eco-region 1) and 65 (eco-region 2) (see Tables 1 and 2). In the same tables an increase in the coefficient of determination as a function of grid size can be seen, which is due to the generalization process caused by larger cell sizes and the resulting decrease in the sample size. The application of the threshold values of 55, 45 and 65, resulted in three burned-unburned images which assured the greatest consistency between datasets concerning burned area (according to the BAIM criterion) and number of active forest fires as detected as thermal anomalies.

Table 1. Coefficients of determination between 'burned area' and 'number of active fires' for different BAIM threshold values and grid sizes. Results are for the whole Galician territory

BAIM	Grid sizes			
	2x2km	4x4km	8x8km	10x10km
30	3.94%	8.27%	8.72%	9.07%
35	8.91%	17.77%	19.43%	21.18%
40	17.11%	30.76%	35.86%	38.08%
45	26.58%	40.36%	48.56%	52.19%
50	42.29%	65.14%	77.87%	81.79%
55	43.20%	66.59%	79.22%	84.22%
60	42.36%	65.86%	78.33%	83.93%
65	41.99%	64.38%	78.76%	82.49%

Table 2. Coefficients of determination between 'burned area' and 'number of active fires' for different BAIM threshold values and grid sizes. Results are for the two different eco-regions

BAIM	Grid sizes							
	Eco-region 1				Eco-region 2			
	2x2km	4x4km	8x8km	10x10km	2x2km	4x4km	8x8km	10x10km
30	35.98%	57.84%	75.70%	78.40%	0.02%	0.57%	1.74%	4.46%
35	45.79%	71.06%	83.04%	88.41%	0.32%	0.39%	1.77%	6.93%
40	50.49%	74.71%	85.01%	89.95%	0.38%	0.94%	3.97%	11.81%
45	51.77%	74.84%	84.96%	90.17%	1.31%	1.55%	6.61%	15.21%
50	49.64%	73.44%	83.78%	89.30%	7.34%	25.26%	39.80%	53.41%
55	48.04%	71.81%	82.91%	88.87%	11.02%	31.03%	48.16%	58.43%
60	46.67%	70.60%	81.65%	87.95%	11.54%	32.18%	48.06%	57.10%
65	45.80%	68.92%	80.68%	85.73%	11.98%	29.40%	54.59%	56.72%

In terms of spectral response in the optical range (visible and infrared), burns are very often confused with water bodies and other low reflective surfaces; furthermore, the present work focuses on forest fires. Consequently, a vegetation mask was needed in order to screen out water bodies, urban or un-vegetated areas and, in turn, produce a reliable burned area map. The selected forest mask was developed from the CLC2000 coverage, a European land cover database at a scale of 1:100,000. The CORINE Land Cover map comprises 85 different classes in the case of Spain; and 13 of those, classified as either 'un-burnable' or 'no-forested', were found in the Galicia region. The mask obtained from this process was applied to previous burned-unburned maps which produced improved results in terms of the map's accuracy. These maps were subsequently converted into vector polygon format.

The Galicia region is 30,000 square kilometers in size, hosting a wide range of ecosystems from the Atlantic to the Mediterranean areas (west to east and north to south). Such spatial variation, combined with the threshold value we used for the whole study area (threshold value of 55), produced an excellent delineation of burned patches in the west part of Galicia, but a

large number of commission errors, especially in the southeast area in our study. As expected, the application of a fixed threshold did not result in burn mapping of homogenous quality; no matter how precisely the BAIM threshold had been defined. Therefore, and to better cope with the diverse environments throughout Galicia, the burn mapping algorithm required the use of threshold values based on climatic and vegetation properties, as the ones that are summarized in the eco-regions map.

Despite the use of two different threshold values for the Galician territory (45 for eco-region 1 and 65 for eco-region 2), some commission errors did still remain on the burned area map. The last step consisted of using the MODIS active fire locations to confirm burned polygons, thus eliminating many 'false burns'. A visual analysis of the MODIS image together with the MODIS active fire locations revealed that most burned areas (which appear darker throughout the MODIS image) contained active fires inside, therefore it was decided to use the latter to screen out clearly unburned polygons as well as small polygons (commission errors). The resulting maps are shown in Figure 2.



Figure 2. On the left, burned area map: patches of BAIM greater than 55 and containing at least one active fire inside. On the right, burned area map: patches of BAIM greater than 45 (within the eco-region 1) or greater than 65 (within the eco-region 2) and containing at least one active fire inside

3.2 Validation of the 500m MODIS-derived burned area map

Final burned area maps (shown in Figure 2) were validated using a 56m AWiFS-derived burned area map that had been produced in a previous research (González-Alonso and Merino-de-Miguel, 2008). The methodology that we developed for the AWiFS-derived scar map does not differ much for the one used in this work, except for the stratification process. For validation purposes, we did compare vector layers that represented the different burned area maps using geo-processing GIS tools. The comparisons were done: (i) between the AWiFS-derived burned area map and the MODIS-derived with one fixed threshold value burned area map, and (ii) between the AWiFS-derived burned area map and the MODIS-derived with two threshold values (one per eco-region) burned area map.

4 RESULTS AND DISCUSSION

4.1 Development of a burned area mapping algorithm using MODIS reflectance and active fire data

Figure 2 shows two burned area maps for the Galicia region (northwest Spain) for the 2006 summer season until the 21st of August. The affected area was 859.50 and 944.75 square kilometres, respectively. As explained in the methodology section, the first steps for burn mapping included BAIM estimation and threshold plus mask application, all of which resulted in a vector layer with 546 polygons that covered a total of 1270.00km², for the first estimation (an single threshold value of 55 for the whole Galician territory), and in a vector layer with 469 polygons that covered a total of 1679.25km², for the second estimation (a threshold value of 45 for the territory in the eco-region 1 and a threshold value of 65 for the territory in the eco-region 2). Although these figures may appear elevated when compared with official statistics (according to the Ministry of Environment the burned area was 930km²), it was decided to keep the threshold values, not only because they produced the best correlation (see Tables 1 and 2) but also because it best delineated the boundaries of individual burns (especially in the west) in spite of producing many commission errors (thousands of small polygons) in the southeast. Some authors propose dynamic thresholds based on the magnitude of one pixel relative to the surrounding pixels or to a time series (Fraser *et al.*, 2000; Roy *et al.*, 2005). For the present work however, it was decided to rely on the fixed threshold values that produced the best delineation and to screen out unburned polygons by using available information on active fires accumulated during the period of study. Active fires were thus used to maintain those polygons where fire had happened with a high degree of certainty, a process which produced 121 and 125 polygons accounting for an area 859.50 and 944.75 square kilometres, respectively.

Prior to thorough validation using the AWiFS-derived burned area map, the obtained results were compared to the official fire statistics from both the Spanish Ministry of the Environment and the Galician Forestry Service. The obtained results tally with data from the Ministry of the Environment (Ministerio de Medio Ambiente, 2006) which record figures of 929.41 km² of burned area for the Galicia region until the 1st of October 2006. Our analysis compared to the official record of burned area per province is presented in Table 3, which shows that high quality results were reached for three of the four provinces.

Table 3. Galicia burned area: figures from the Ministry of Environment versus reached results, areas expressed in squared kilometers per province; relative difference between both sets of data

	One threshold value			Two threshold values		
	Ministry of Environment	Reached results	Relative difference	Ministry of Environment	Reached results	Relative difference
A Coruña	345.04	376.75	-9.19%	345.04	432.25	-25.27%
Lugo	60.80	16.75	72.45%	60.80	17.50	71.22%
Orense	120.67	128.00	-6.07%	120.67	101.50	15.88%
Pontevedra	402.90	338.00	16.14%	402.90	393.50	2.33%
Galicia	929.41	859.50	7.53%	929.41	944.75	-1.65%

The case of Lugo, where more than half the 'burned area' was missed, was analyzed concluding that either there had been a wildfire between the 21st of August (AWiFS image) and the 1st of October (Ministry of the Environment data) or there had been an early season fire (or fires) after which the vegetation had partially recovered. According to the Galician Authorities (Xunta de Galicia, 2007), the affected area for the whole year was 938.87 square kilometers.

4.2 Validation of the 500m MODIS-derived burned area map

Validation of the two 500m MODIS-derived burn maps was carried out in comparison with the 56m AWiFS-derived burn map. For doing so, we used the polygon vector format files that compromises all the burned patches as detected by the different maps involved in the analysis (an example in shown is Figure 3). The geo-processing, that was straightforward, consisted of doing some intersections between layers. The area detected as burned in both maps (AWiFS and MODIS) referred to the AWiFS-derived map, was of 68.00% for the MODIS-derived map based on one fixed threshold value and, of 72.97% for the MODIS-derived map based on two fixed threshold values (one per eco-region). Results are quite satisfactory within the limits of the MODIS image spatial resolution. As shown in Figure 3, all large patches, detected by means of the AWiFS data, were also classified as burned using the MODIS data. Main differences between the two maps were found inside the patches (AWiFS-derived map is more precise not only delineating but also detecting unburned pixels inside a patch) and concerning the detection of small polygons.

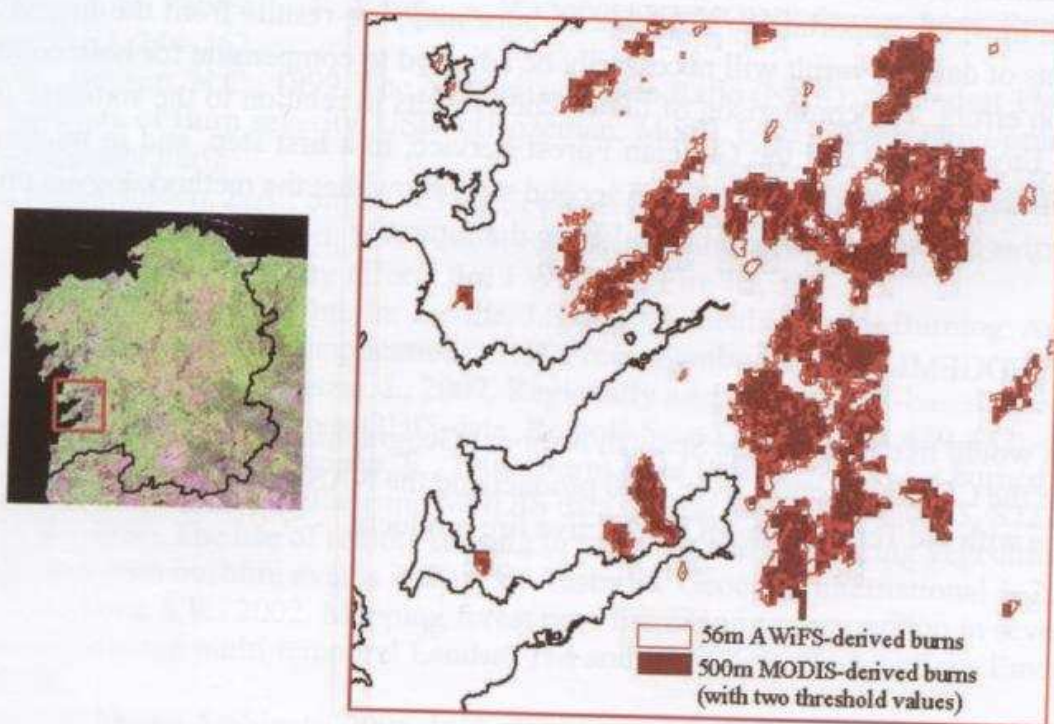


Figure 3. Burned area map: patches of the 56m AWiFS-derived burned area map (light red) and patches of the 500m MODIS-derived burned area map (dark red)

5 CONCLUSIONS

This article presents an analysis on the affection of fire to the forested lands of Galicia (north-west Spain) during the 2006 summer season (until the 21st of August 2006). It starts presenting a semi-automatic algorithm for burned area mapping that uses remote sensing techniques and data and that was successfully applied to the Galicia region (Spain). For the first step, it uses satellite information from four different parts of the spectrum (NIR, SWIR, middle- and thermal-infrared, or MIR and TIR, respectively). We developed a methodology that is based on the combination of a spectral index with active fire locations, which builds on previous research works (Roy *et al.*, 1999; Fraser *et al.*, 2000; Al-Rawi *et al.*, 2001; Pu *et al.*, 2004) and also introduces innovations like the use of the BAIM index (Martín *et al.*, 2006) and MODIS data. To be more precise, the BAIM index (based on NIR and SWIR bands) thresholding is used to produce a 'burned-unburned' map while the active fire series (based on MIR and TIR bands) are used to calculate the threshold values but also to remove falsely detected burns. The overall result is a close approximation to actual burn boundaries within the limits of the MODIS pixel size. There are five advantages to the method presented in this paper which are worth pointing out here: (i) pre-processing and processing of data is rapid, (ii) no field data is needed, (iii) not much human-based decision-making is required (objective method), (iv) it is easy to implement and (v) it has been successfully applied at least once on a regional scale.

The methodology in question here has produced reliable results largely due to its use of best correlation between two sets of data, each one coming from a different part of the spectrum. On the one hand, the BAIM index is estimated using information from the NIR and SWIR channels, where reflective processes are dominant. On the other hand, active fire data is elaborated using information from the emissive part of the spectrum, where the MIR and TIR channels are located. It is however important to note that as burn mapping results from the intersection of these two sets of data the result will necessarily be adjusted to compensate for both commission and omission errors. The comparison of the reached results in relation to the statistics from the Ministry of Environment and the Galician Forest Service, in a first step, and in relation to the 56m AWiFS-derived burned area map, in a second step, show that the methodology is promising although further improvements will be studied in the future.

ACKNOWLEDGEMENTS

The authors would like to thank the Spanish National Geographic Institute (IGN) for helping us in the use of the CORINE Land Cover 2000 product and the NASA / University of Maryland for providing us with the Terra/Aqua MODIS active fire products.

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